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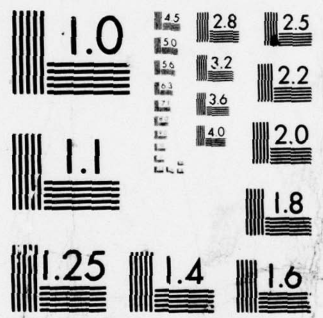

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Generation of a Reversed Field Configuration Without an Applied Magnetic Field

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A rotating relativistic electron beam, charge- but not current-neutralized and exceeding the Alfven limit, has been propagated down a closed metal tube in the absence of an external guide field. The radial equilibrium is determined by the self fields of the beam and the induced wall currents. The 100 nsec duration beam, upon leaving the system, induces plasma currents that maintain a field reversed configuration for 18 ~~μsec~~. microseconds

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GENERATION OF A REVERSED FIELD CONFIGURATION WITHOUT AN APPLIED MAGNETIC FIELD

This letter describes experiments in which a plasma in a reversed-field configuration, with both axial and azimuthal magnetic field components, has been produced inside a closed metal tube in which there is initially no field. The configuration is generated by a rotating relativistic electron beam injected into neutral hydrogen gas, and maintained by plasma currents induced when the beam leaves the system. Previous studies of similar beam-generated configurations[1-4] have all used an initial, externally applied, magnetic field. Reversal of the applied field by up to four times has been observed[3], with a lifetime determined by the L/R decay of the currents in the fully ionized plasma ($n_e = 5 \times 10^{15}$ cm^{-3}, $T_e \sim 3 - 5$ eV)[4].

Radial equilibria are possible for both beams and plasmas inside a flux-conserving cylinder without an applied field. Yoshikawa[5] has described the equilibrium of a rotating beam in its self-induced fields, and has shown that in this configuration the beam current, I, is not subject to the Alfven limit, $I < I_A = 17000\,\beta\,\gamma$ Amperes. Arbitrarily large currents can then flow in a configuration that becomes increasingly force-free as $I \gg I_A$.

To produce a rotating beam, an annular beam is first created by

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a diode in an axial magnetic field. The field is brought to zero in a short distance from the anode by using a suitable arrangement of coils to divert the field lines radially outward. (This is known as a 'half-cusp'.) The interaction of the axial velocity of the beam with the radial component of the field gives the beam an azimuthal component of velocity;[6] the resulting hollow rotating beam thus generates both axial (B_z) and azimuthal (B_θ) magnetic fields. If the beam is injected into a closed metal cylinder, flux conservation requires that there should be an axial magnetic field, B_{zo}, between the beam and the wall in the opposite direction to the axial field, B_{zi}, inside the beam. The equilibrium radius of the beam is then determined by the balance of the magnetic and centrifugal forces on the electrons, and flux conservation.

The beam is injected into neutral gas, which is ionized by collisions with the beam electrons and the strong electric field induced by the rapidly-rising magnetic field at the beam head. The gas pressure may be chosen so that the resulting plasma is sufficiently dense to charge-neutralize, but not current-neutralize, the beam. Thus the magnetic field of the beam is carried into the plasma. During the beam pulse the plasma is heated and its conductivity increased, so that when the beam leaves the system, currents are induced in the plasma to conserve the magnetic flux. The field of the beam is thus 'frozen into' the plasma, and will remain for a time limited only by resistive dissipation of the plasma currents.

This sequence of events has been observed in the experimental apparatus shown in Fig. 1. An annular relativistic electron beam from the modified Triton accelerator[7] ($V = 900$ kV, $I = 110$ kA, $\tau = 100$ nsec FWHM) is injected through a half cusp, located at $z = 0$, into a 14.6 cm diameter stainless steel tube containing neutral hydrogen gas. The half cusp is formed by a solenoidal coil around the cathode, which contains a 15 cm long ferrite cylinder, and a flat pancake coil, situated 0.3 cm from the anode foil and .2 cm from a 1.3 cm thick aluminum plate, which excludes magnetic flux during the 400 μsec risetime of the current in the coils. Thus, the field lines emanate from the cathode perpendicular to the emission surface and pass out between the pancake coil and aluminum plate, resulting in a measured B_r axial extent (FWHM) of 1.8 cm. The system is terminated with a transparent brass screen at $z = 65$ cm.

Typical results are shown in Figure 2. The traces show values of B_θ at $r = 6.3$ cm, B_z at $r = 6.3$ cm (i.e., B_{zo}) and B_z on axis (i.e., B_{zi}) as measured by three miniature magnetic probes. B_{zo} and B_{zi} are in opposite directions and indicate that a field-reversed configuration persists for 12 μsec. End-on framing photographs show the plasma has an annular profile (typical mean radius 3.9 cm, annular width 1.5 cm) and is clearly separated from the tube wall (radius 7.3 cm). As the configuration decays, the plasma radius does not change, unlike in the guide field case[4]. This is to be expected, since without the applied, all the confining fields decay with the plasma.

The equilibrium position of the plasma differs from that of the beam due to the absence of a centrifugal force term in the radial balance. If the plasma pressure is low, the plasma currents are force-free. The equilibrium radius of a thin plasma layer can then be simply found from pressure balance:

$$B_{zi}^2 = B_{zo}^2 + B_\theta^2, \tag{1}$$

combined with flux conservation:

$$B_{zi}\, r_p^2 + B_{zo}(r_w^2 - r_p^2) = 0, \tag{2}$$

where r_p and r_w are the radii of the plasma and wall, respectively. These equations lead simply to

$$\frac{r_p}{r_w} = \left(\frac{1-\cot^2\alpha}{2}\right)^{\frac{1}{2}} \quad ; \quad \frac{B_{\theta w}}{B_{zo}} = \left(\frac{2}{\tan^2\alpha - 1}\right)^{\frac{1}{2}} \quad , \tag{3}$$

where $B_{\theta w}$ is B_θ at the tube wall, and α is the pitch angle of the helical plasma current (note that this model predicts no equilibrium unless $\alpha > 45^\circ$). The pitch angle of the beam may be adjusted by changing the magnetic field in the half-cusp; increasing the field winds the beam into a tighter helix, increasing both B_{zo}/B_θ and the plasma radius. In Fig. 4, B_{zo}/B_θ, measured by magnetic probes at $r = 6.3$ cm, is plotted against the plasma radius, measured from framing photographs. Both quantities are obtained at $t = 2\ \mu$sec. The solid curve is the prediction of the model in Eq. (3), and good agreement with the data is seen. The apparent limitation of the plasma radius at 4 cm was found to be due to the beam hitting the edge of the aluminum plate at the higher half-cusp magnetic fields, resulting also in reduced axial current and a marked decrease in plasma thickness.

The B_{zi} probe, used to verify Eq. (1) and (2), was found to have a perturbing effect on the plasma and was removed for subsequent measurements, since knowledge of $B_{\theta w}$, B_{zo} and r_p is adequate to determine the configuration. With the probe removed, the configuration is created uniformly along the full 65 cm length of the tube and persists for approximately 18-20 μsec. This observation is in keeping with side-on streak photography, which shows the light emitting region has a similar axial extent. In Fig. 6, signals from identical magnetic probes at z = 20, 40 and 60 cm are presented. Note that immediately after passage of the beam (t = 0), the magnetic fields are uniform along the length of the tube. B_θ is shown in units of axial current on the right-hand scale. The current of 75 kA exceeds the Alfven current (I_A = 43 kA for 900 kV electrons), thus confirming the prediction of Yoshikawa[5]. This net current is, however, only 68% of the diode current; this loss may be due to some current-neutralization of the beam or to some loss in transmission through the half-cusp.

As the configuration decays, B_θ changes uniformly along the tube, suggesting the configuration is continuous over its length. However, B_{zo} at z = 60 cm increases by a factor of two within the first 4 μsec, indicating the rotating currents are piling up against the end screen. As both B_{zo} at 20 and 40 cm do not decrease, evidently magnetic energy is being transferred from the azimuthal field to the axial field, and is indicated by the rapid early decrease in B_θ. This observation can be explained by visualizing the plasma currents as a helical coil, which contracts in a manner to minimize its magnetic energy. (The tendency to collect at the end wall is probably due to the asymmetry introduced by a small residual magnetic field that has penetrated the aluminum cusp plate.) The overall lifetime of the configuration is consistent with the classical L/R decay time of the plasma currents, assuming an electron temperature of ~ 7 eV; it is also comparable to the time for plasma to free stream out the ends of the system.

The configuration strength (in terms of B_{zo}) and lifetime (full width), as determined by a magnetic probe at $z = 20$ cm, are plotted as a function of gas pressure in Fig. 5. The data points include measurements taken with (triangles) and without (circles) a 1 mm diameter tungsten wire inserted across a radius of the tube at $z = 30$ cm. The results are unaffected by the presence of the wire; since the wire would absorb any trapped beam electrons within 500 nsec, this confirms that the field-reversed configuration is indeed maintained by plasma currents alone.

Both lifetime and strength of the configuration have maxima at hydrogen pressures between 100-150 mTorr. Below 100 mTorr insufficient plasma is produced to charge-neutralize the beam, which will not propagate beyond $z = 20$ cm. As the pressure is increased above 150 mTorr the beam is probably current-neutralized to an increasing extent, while the energy deposited by the beam has to be shared by more particles, resulting in a lower electron temperature, T_e. If limited by classical resistive decay, the lifetime of the configuration, $\tau \propto T_e^{3/2}$. Assuming $T_e \propto n^{-1}$, leads to $\tau \propto n^{-3/2}$. The solid line in Fig. 5(a) represents this $n^{-3/2}$ scaling, and is in quite good agreement with the data.

The significance of these observations is that a rotating beam, charge- but not current-neutralized, with a current $I > I_A$, can (i) propagate with an equilibrium determined by its self-fields, as predicted by Yoshikawa[5] and (ii) set up a reversed field plasma configuration by inducing currents in the plasma and wall of a closed, initially field-free, metal tube.

In the present experiments, the configuration resembles a linear reversed-field pinch. It is possible to envisage extensions of this technique to produce plasma configurations with closed field lines. These could be further heated by the injection of intense neutral, electron, or ion beams; or by an imploding liquid metal liner, as in the NRL LINUS fusion concept.[8]

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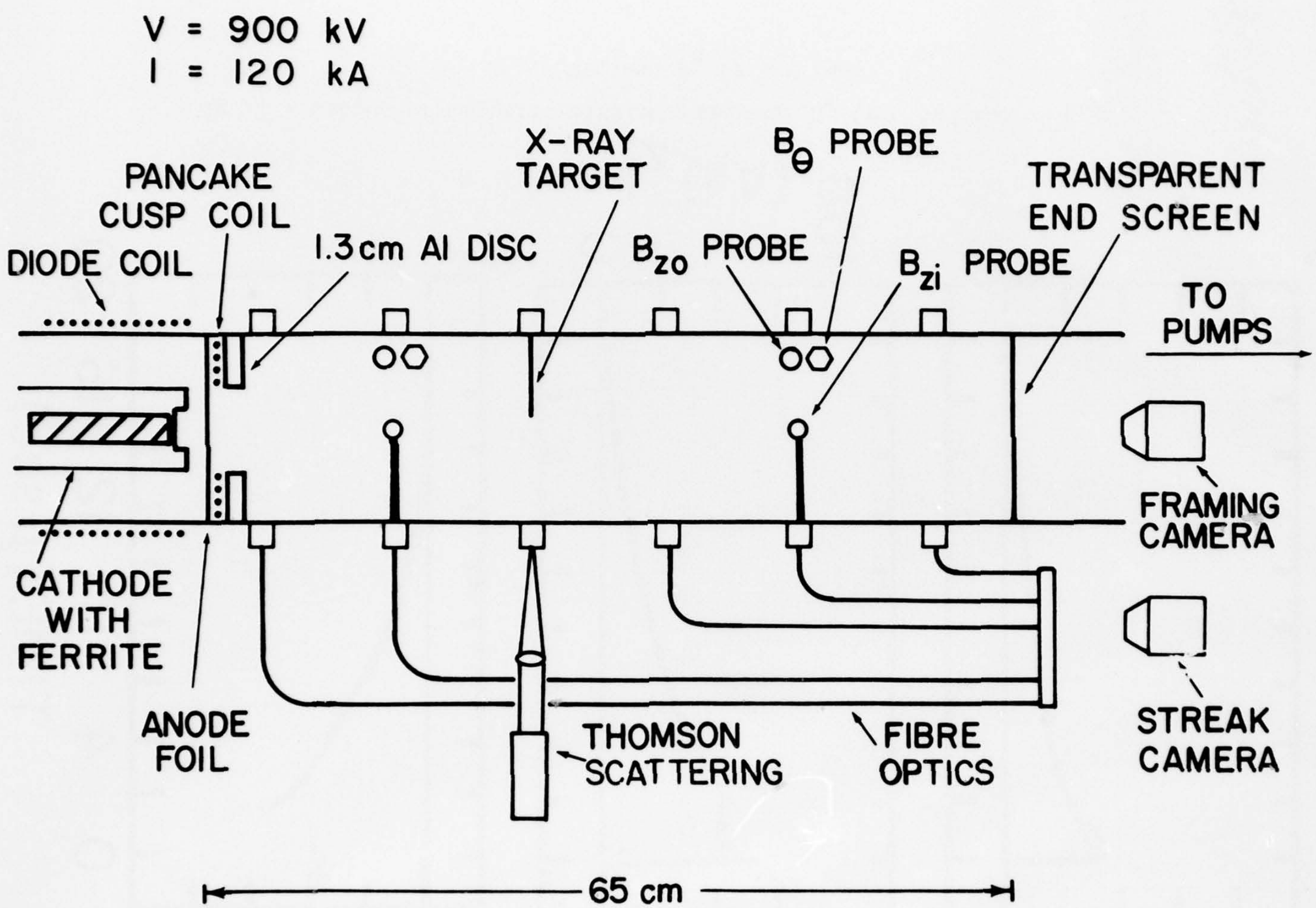

Fig. 1 - The experimental facility.

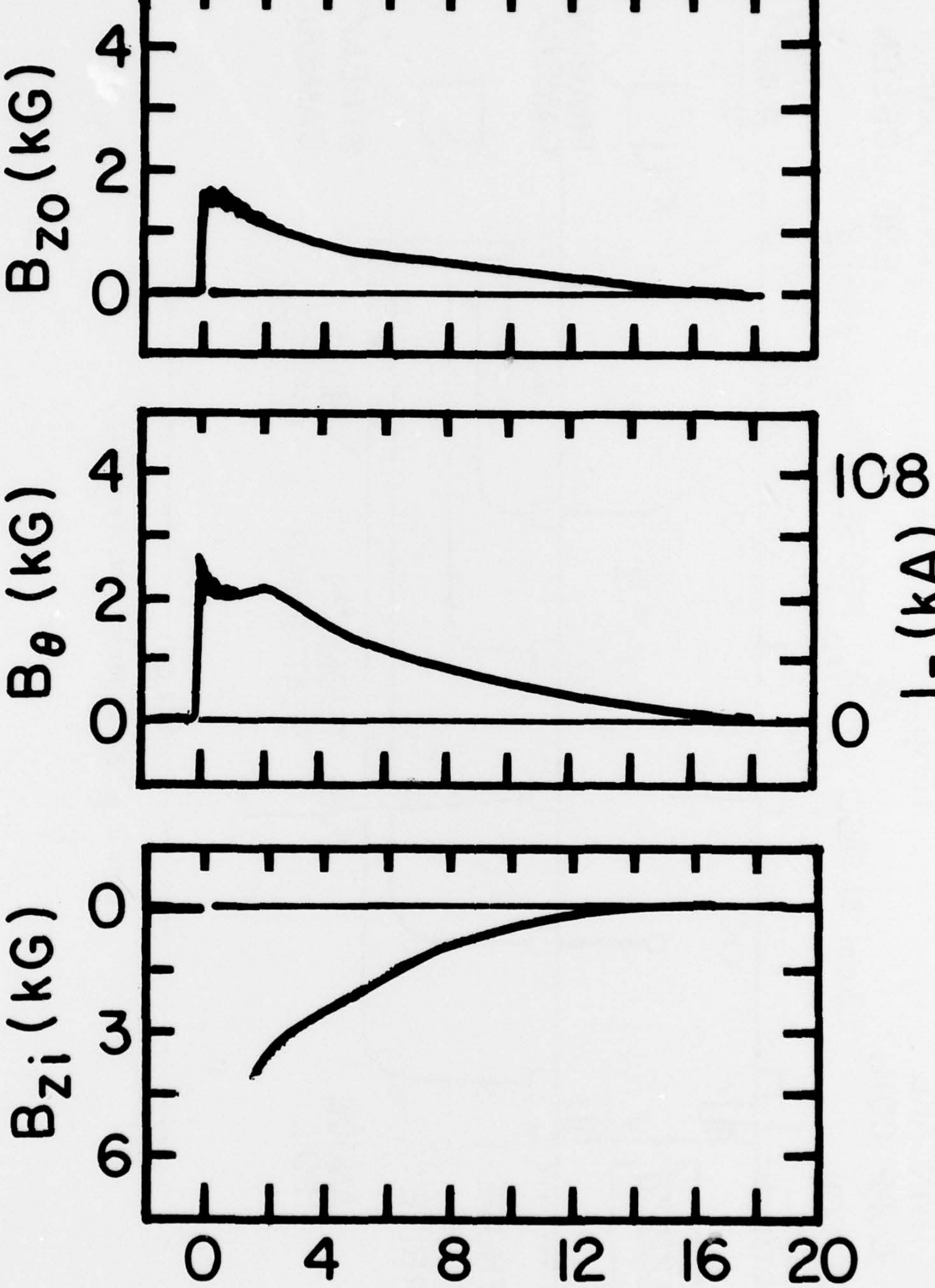

Fig. 2 - Output of magnetic probes measuring B_z (r = 6.3 cm) ≡ B_{zo}; B_θ (r = 6.3 cm); and B_z (r = 0 cm) ≡ B_{zi}.

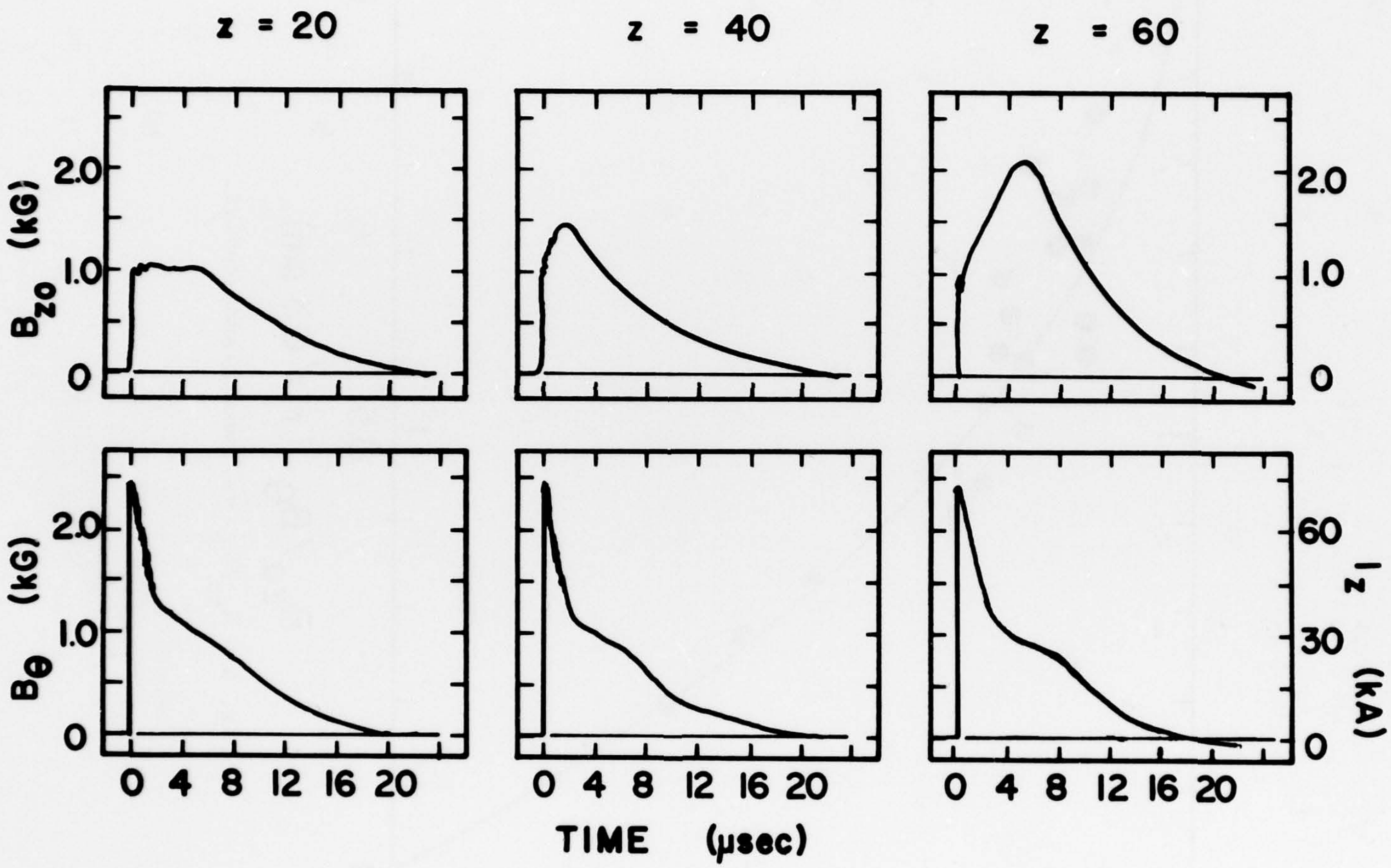

Fig. 3 - Magnetic probes measuring B_{zo} (upper) and B_{θ} $(r = 6.3)$ at three axial positions.

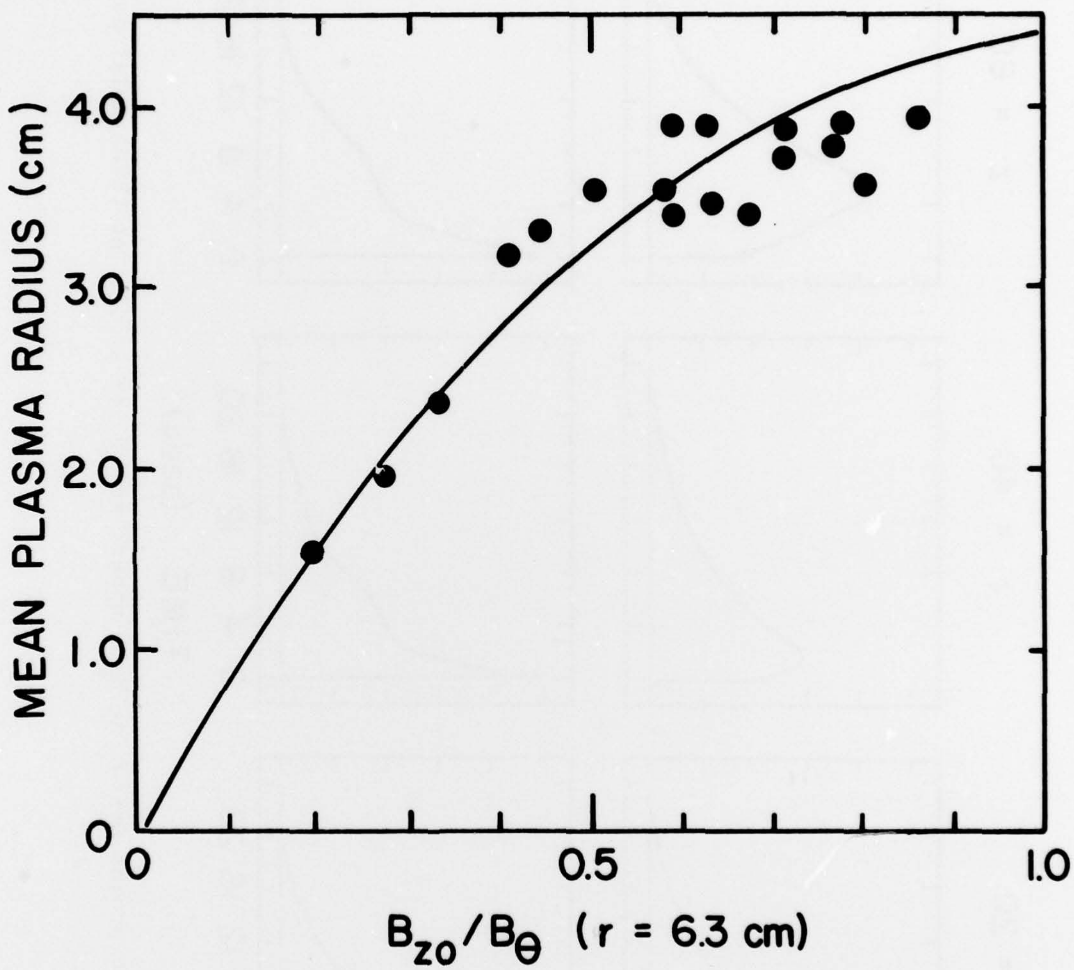

Fig. 4 - B_{zo}/B_{θ} vs. mean plasma radius.

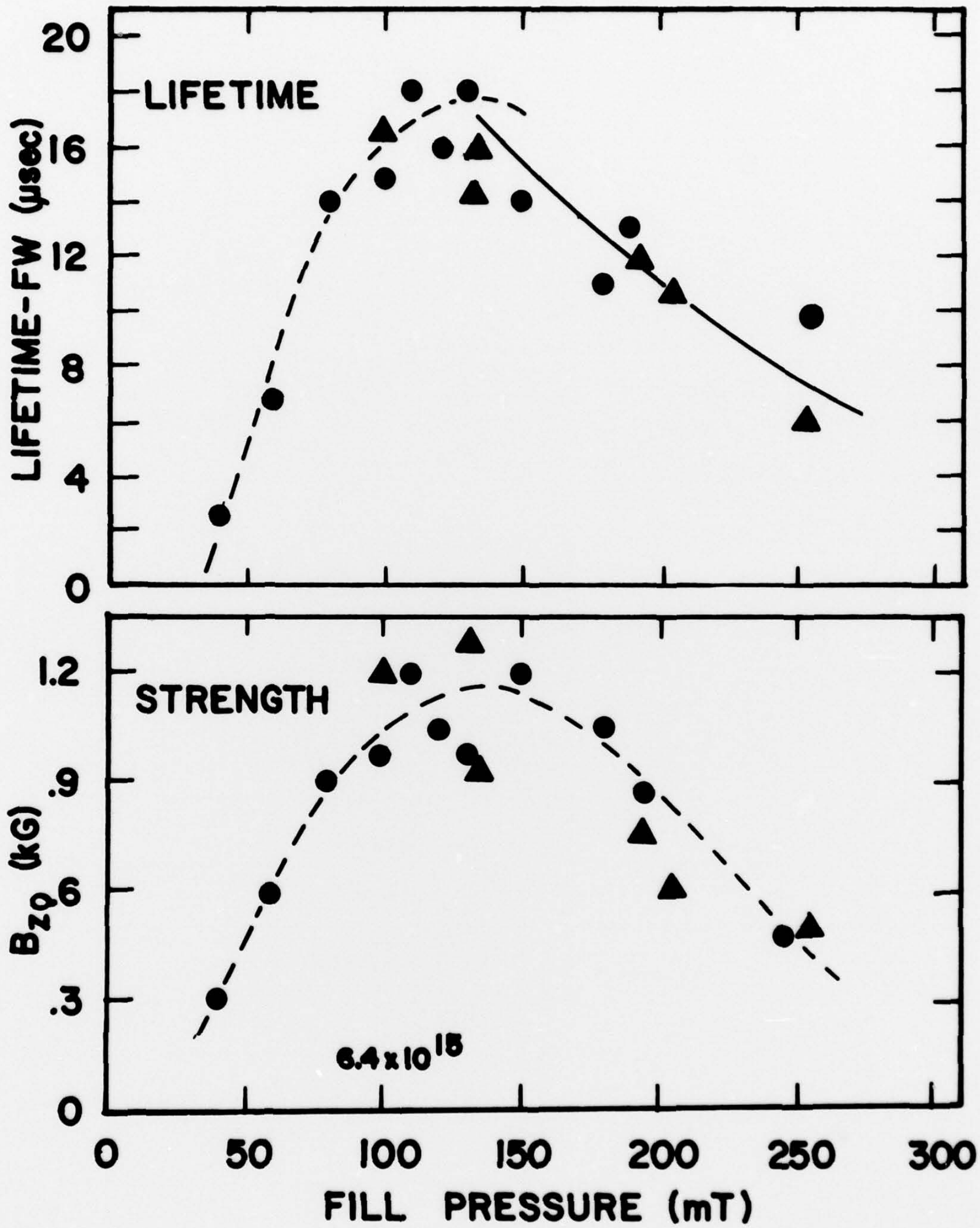

Fig. 5 - Layer lifetime and strength vs. fill pressure.